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ENERGY SAVINGS OBTAINABLE THROUGH PASSIVE SOLAR TECHNIQUES

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ABSTRACT

A passive solar energy system is one in which the thermal energy flow is by natural means, that is by radiation, conduction, or natural convection. The purpose of the paper is to provide a survey of passive solar heating experience, especially in the U.S. Design approaches are reviewed and examples shown. Misconceptions are discussed. Advantages are listed. The Los Alamos program of performance simulation and evaluation is described and a simplified method of performance estimation is outlined.

INTRODUCTION

During the period of 1976-1979 passive solar heating of buildings emerged rather suddenly within the United States from the status of a curiosity to recognition as one of the most practical and effective means of using solar energy. Many of the factors which have caused this to happen are also present in Portugal and it would seem that such an awakening might also be possible here. Passive solar offers a simple, economical, comfortable and reliable means of building heating that is particularly suitable to the range of latitudes where most of the Portuguese population resides. The bulk of the heating loads can be easily offset by solar gains through effective architectural use of materials normally employed in construction.

By careful consideration of building orientation, treatment of glazing, storage of excess heat in building mass, shading, and ventilation, a building can be designed to be quite climatically adaptive, absorbing solar gains during a winter day and storing through to the night and yet rejecting summer sun. Passive cooling effects can also be achieved by control of radiation losses, evaporation, ventilation, and especially the use of building mass heat capacity to average diurnal temperature swings thus reducing afternoon overheating.

THE U.S. EXPERIENCE

By 1976 a handful of experimental buildings had been built based on very explicit passive solar heating concepts. These were isolated and almost

*Work performed under the auspices of the U.S. Department of Energy, Office of Solar Applications.

independent designs based more on physical intuition than mathematical analysis. They were located in such varied places as the Pyrenees of southern France, the New England and Southwestern parts of the U.S. and Liverpool, England. There had been several prior passive buildings by Morse in Massachusetts, Keck in the midwest U.S., and the M.I.T. researchers but they had gone largely unheeded.

The period from 1973 to 1976 saw an intense interest in active solar energy development in response to energy curtailments and a sudden general awareness of the finiteness of world energy supplies. This led to major U.S. federal government expenditures in solar energy and the emergence of a solar industry comprised primarily of small business. By the end of 1978 the total number of solar installations was estimated to be 100,000 dominated by swimming pool and domestic hot water heating applications. However, little note was taken of passive solar approaches in a rush to commercialize solar through the establishment of an industry which saw little to gain through promotion of passive concepts.

Almost in parallel with the active system effort, a small but determined group began an investigation of passive solar approaches. A series of three well-attended national passive solar conferences was held in the U.S. in May 1976 (Albuquerque, New Mexico), in March 1978 (Philadelphia, Pennsylvania), and January 1979 (San Jose, California). The proceedings of these conferences (1,2,3) plus several papers given at annual conferences of the ISES, American Section (4, 5) contain a wealth of scientific information on passive system analyses and performance evaluations. Second and third generation passive solar buildings have been built and reported. A growing enthusiasm for passive approaches has emerged strongly supported by regional solar energy associations, architects, grassroots and alternative energy groups, appropriate technology enthusiasts, and ecologists.

The last few years have been characterized by a plethora of energy studies and policy reviews. Virtually every such study reported in 1979, including the much-vaunted governmental Interagency Domestic Policy Review, has strongly recommended that major attention be given to passive solar heating. The Department of Energy (DOE) has singled out two solar technologies to be emphasized in a major commercialization program: water heating and passive space heating. The Department of Housing and Urban Development conducted a special Passive Solar Design Competition for residential housing and awarded $1,300,000 in prizes to 162 of the 550 applicants that qualified. The research and development budget for passive solar heating and cooling has grown from $135,000 in 1975, to $400,000 in 1976, to $2,800,000 in 1978 to a planned $4.2 million in 1979, and $16.2 million in 1980.

PASSIVE SOLAR DESIGN APPROACHES

A passive solar energy system is one in which the thermal energy flow is by natural means, that is by radiation, conduction, and natural convection. Passive systems are distinguished from active systems by the absence of a mechanical pump or fan needed to force the flow of a heat exchange fluid. In most, but not all cases, a passive system is very strongly integrated into the architecture of the building. Often, the materials of the building serve a dual purpose. For example, an equatorially oriented window serves to collect the sun's heat and also provides both visual access to the outside and natural daylighting. Also, the walls of the building often serve for both thermal storage and structural support.

Two different schemes for classifying passive solar systems have been used. One is a functional or generic classification in which the relationship of solar gain, thermal storage, and the heated space are classified according to the categories: 1) direct, 2) indirect, and 3) isolated. A second classification scheme, which has been used more often, defines passive system types according to the physical configuration. In this scheme the buildings are identified according to the categories, a) direct gain, b) thermal storage wall, c) attached sun space, d) thermal storage roof, and e) convective loop. Both classification schemes are very useful and can augment one another; used together they form a powerful vocabulary for describing various passive design approaches. These two classification schemes are described in more detail below.

<u>Physical Categories</u>

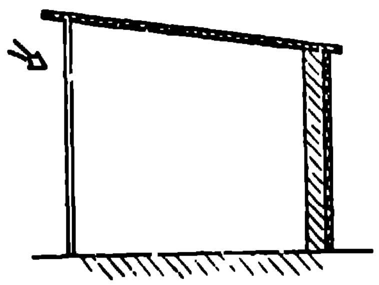


Fig. 1. Direct Gain. Sunlight enters the heated space, is converted to heat at absorbing surfaces, and is dispersed throughout the space and to the various enclosing surfaces and room contents.

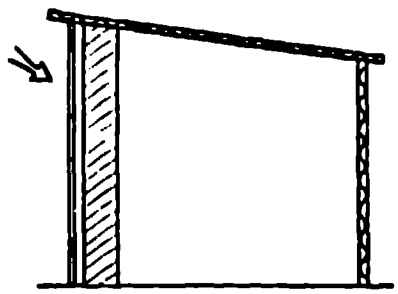


Fig. 2. Thermal Storage Wall. Sunlight penetrates glazing and is absorbed and converted to heat at a wall surface interposed between the glazing and the heated space. THe wall is usually masonry (Trombe wall) or containers filled with water (water wall), although it might contain phase-change material.

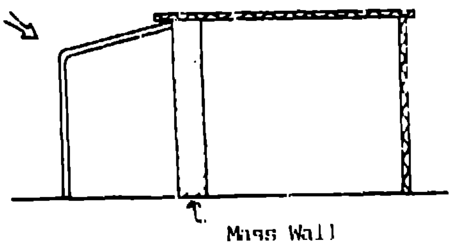


Fig. 3. Attached Sunspace. This is a combination of direct gain and thermal storage wall approaches. The building consists of two thermal zones; a direct-gain "sunspace" and an indirectly heated space, separated by a thermal storage wall. The "sunspace" is most frequently used as a greenhouse in which case the system is called an "attached greenhouse" or "solar greenhouse."

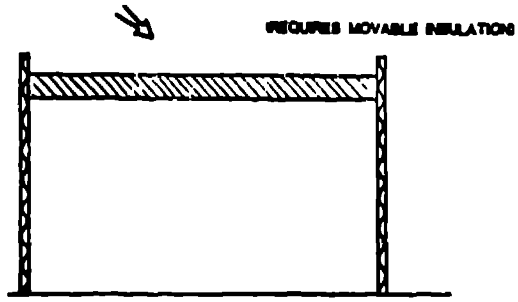


Fig. 4. Thermal Storage Roof. This is similar to the thermal storage wall except that the interposed thermal storage mass is located on the building roof.

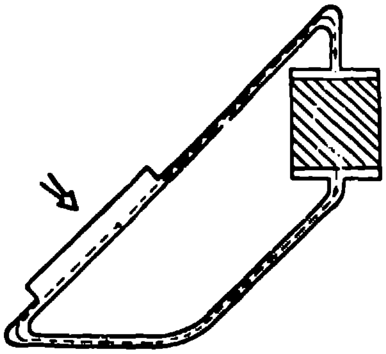


Fig. 5. Convective Loop. This approach is most akin to conventional active systems in that there is a separate collector and separate thermal storage. It is a passive approach, however, because the thermal energy flow is by natural convection.

GENERIC CATEGORIES

1. Direct. Same as above, Fig. 1.

2. Indirect. Sunlight is absorbed and stored by a mass interposed between the glazing and the conditioned space. The conditioned space is partially enclosed and bounded by the thermal storage mass so that a strong natural (and uncontrolled) thermal coupling is achieved. Examples of the indirect approach are the thermal storage wall, thermal storage roof, and the northerly room of the attached sunspace, as depicted in Figs. 2, 3, and 4.

3. Isolated. This is an indirect system except that there is a distinct thermal separation (by means of either insulation or physical separation) between the thermal storage and the heated space. The convective loop, as depicted in Fig. 5, is in this category. The thermal storage wall, thermal storage roof, and attached sunspace approaches can also be made into isolated systems by insulating between thermal storage and the heated space.

Discussion

The physical categories listed above are frequently used in descriptions of passive systems because they are easily visualized and most quickly convey the concepts and physical principles embodied in the most common passive designs. However, they lack generality and a large catalog of different approaches and associated physical descriptions can be expected to emerge. The generic categories are so general in nature that they can be expected to survive as useful ways of describing quite a broad range of concepts. Furthermore, they apply with equal ease to natural cooling concepts as well as solar heating, whereas all the physical categories listed above, except the thermal storage roof, are specifically solar heating concepts. Reductions in cooling load, due to added mass in the building, may well be an added benefit, but this does not usually drive the design. Addition of ventilation cooling by means of a thermally driven natural convection chimney may also be incorporated.

These descriptive categorizations overlap but can be used together. For example, one could easily refer to a mix of isolated thermal storage water wall and convective loop--such a combination has, in fact, been built and shown to work well.

Hybrid Systems

Combinations of active and passive design approaches are referred to as "hybrid" systems. A common example is the use of a passive collector such as a greenhouse in conjunction with a fan-forced rock bed thermal storage.

MYTHS

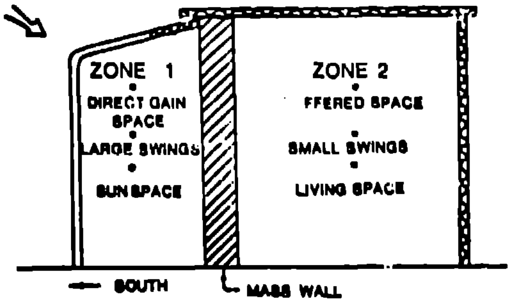
Passive solar is not much understood and a number of misconceptions have grown up around false notions. Among these are:

1. "Passive solar will work well only in privileged regions, such as the American southwest." Both experience and analysis refute this. Successful applications have been demonstrated in frigid Wyoming, cloudy and cold New England and cloudy, grey Liverpool, England. Calculations for a 45 cm Trombe wall, used with night insulation, indicate the following energy savings:

	Latitude	Heating load ^{o}C-days	Solar Heating Fraction	Net Yield kWhr/m^2-yr
Boston, Massachusetts	42^{o}	3130	48%	303
Albuquerque, New Mexico	35^{o}	2420	71%	346
Madison, Wisconsin	43^{o}	4370	42%	370
Seattle, Washington	48^{o}	2460	54%	268

The area of the wall is 1/4 of the floor area of the house which has a total loss coefficient of 2.1 W/^{o}C per sq meter of floor area (exclusive of the Trombe wall) and maintained within the range of 21.1^{o}C to 26.7^{o}C. Building internal heat sources (people, lights, appliances, etc.) are assumed to account for 2.7^{o}C of the temperature increase.

2. "Occupants of passive solar buildings must sacrifice comfort. Temperature swings are excessive and uncontrollable." Although this certainly can be the case, good design practice can prevent it. If a large solar fraction is desired in a cold climate, a direct gain building can be expected to experience clear-day swings of at least 5^{o}C and more likely 10^{o}C. However, a thick (45 cm +) unvented Trombe wall with thermostatic auxiliary backup can provide a very stable internal environment and at the same time a 70-80% solar contribution. One very effective design approach is to separate the building into two zones as shown below.



The direct-gain Zone 1 will experience large temperature swings (10 to 15^{o}C on a clear day) but provides a very suitable space for an air lock entryway, a transit area, an atrium or a greenhouse. Zone 2, by contrast, can be very stable in temperature and is more suitable as a high-comfort living zone.

Even finer zoning can be used to locate closets, pantries, bedrooms, and living rooms according to individual comfort requirements.

3. "Occupants of passive solar buildings must be very involved in the operati of the system." Again, this is a matter of choice. One can design in hand-operated movable insulation, for example, or hand-closable vents. They can, however, be automated on a thermostat or not used. Most buildings do rely on opening windows for ventilation cooling during warm, sunny spring and fall days but this is a natural and familiar aspect of most houses.

4. "Passive concepts are good only for new construction, not for retrofit." In fact, passive solar is very appropriate in modifications to existing buildings, and at least one-half of the existing passive applications are retrofits. There are four particular approaches which are most suitable:

a. Adding south-facing windows. This provides additional direct gain to a structure which may have very adequate thermal mass built in, especially if it is an older building.

b. Adding a solar greenhouse. The attached solar greenhouse is proving to be a very popular addition, as much because of the added food-growing potential, natural winter humidity and ambience provided as for the extra heat.

c. Adding a convective-loop air heater outside an existing south-facing insulated wall. These are lightweight and inexpensive and are especially effective because they can be built to shut off at night by means of a simple passive backdraft damper. They can be used on apartments or other multi-story structures.

d. Glazing an existing south-facing masonry wall. Thermocirculation vents can be cut through or not as desired, depending on whether the building currently requires major daytime heating.

A particular advantage to passive solar retrofit applications is that one can do a little or a lot or do several small additions in sequence.

5. "There is no evaluation base for passive solar." While it is true that there is more data on active system performance, the results from passive buildings, though less complete, are more encouraging. Data from the MIT II test rooms (1949), the St. Georges School (1974), and the Trombe-Michel Odeillo house (1975) have shown very good performance. Performance of dozens of second and third generation buildings, some well instrumented and some where only meager evaluations have been made, all show large energy savings. The pattern is consistent and the message hard to misunderstand--the results confirm or exceed predictions.

6. "The building must be fully backed up with a conventional heating system sized for the design load." This may be the case in some climates, but the low peak heating requirements of several buildings indicate that a significant reduction in peak heating requirements may be obtained in a passive solar building. This is due to two effects:

a) The long time response of a building with a low loss coefficient and a large mass tending to carry over for three or four days, bridging the gap between periods of solar gain.

b) The efficient collection of very low levels of solar radiation even during adverse weather. There are few days without at least 500 Wh/m^2 of incident solar radiant energy; with this much input night-insulated double glazing will be just neutral at an average temperature difference of 10^oC.

ADVANTAGES

Low Cost

Experience to date in the U.S. is that the incremental add-on installed cost of passive solar systems generally falls within the ranges indicated below, where the cost is given per unit area of collection glazing.

Direct Gain	$20-120/m^2	Thermal storage roof	$100-280/m^2
Thermal storage wall	$80-200/m^2	Convective loop	$ 50-80/m^2
Attached sun space	$50-160/m^2		

These costs vary depending on where and how the building is constructed, the materials used, the workmanship and finishing, and whether or not some means are provided to insulate against losses at night. The cost of night insulation itself is generally in the range of $20 to $100 per sq meter and is included in the ranges given above.

One of the reasons that costs tend to be low for passive systems is because the materials are available, the infrastructure required for the manufacture and distribution of these materials is in place, and builders are familiar with their use. The most common of these materials are glass, other glazings, and masonry. Another reason that costs are low is that the passive elements frequently serve two functions so that their cost can be written off against both functions.

Ease of Natural Operation

High reliability of passive solar designs is attributable to the lack of moving parts and the use of conventional materials. Since there is very little mechanical equipment there is very little to go wrong. Most of the materials which are associated with passive solar design are normal construction materials used within their normal operating range which have already been long and well tested. The two most common materials, glass and masonry, are the elements of the building which can be expected to last the longest under normal conditions.

Thermal Comfort

Perhaps the most comfortable way to heat a building is with a large radiant panel operating at low temperature. Heat fluxes are relatively low, there are no hot spots or cold spots to be expected, drafts are eliminated, and there is no noise. A well insulated room can be heated easily by maintaining any one of the side or floor surfaces at a temperature no greater than 27°C. A particular benefit of radiant heating from a side wall surface is the natural convection of air within the room which occurs between the heated surface and the other slightly cooler surfaces. The convective current is so slow as to be imperceptible to the occupants of the room but sufficiently strong to maintain good mixing of the air and prevent stratification. This type of radiant heating is normally associated with the thermal storage wall and direct gain passive approaches.

It is also well established that it is more efficient to heat a space radiantly than by heating the air. The effective comfort temperature is made up about equally by the mean radiant temperature and by the air temperature. Thus if the mean radiant temperature can be maintained high then the air temperature can be maintained relatively low and still achieve a comfortable condition. Thus the heating of air which infiltrates the building, which accounts for a very significant fraction of the energy requirements of a modern well-insulated building, will be significantly lower in a space which is heated predominantly by radiant energy.

One must be careful in passive solar designs to avoid large cold surfaces within the room in order to avoid the opposite effect described above. Large glass areas seem especially cold in a room and require relatively high air temperatures to offset their depression on the radiant environment. Thus the designer of direct gain systems is led to consider movable insulation systems, drapes, triple glazing, or other means of protecting the room occupants from cold glass surfaces.

Few Needs for Certification

For all of the reasons given above there are few needs for certification of equipment used in passive systems. Procedures for certification have already been established for most of the common construction materials used. And nothing about the application of these materials in passive systems should require an extension of the certifications now in effect.

However, new passive solar components will be developed--such as glazing assemblies, movable insulation assemblies, and other packaged devices--which will require established certifications.

Aesthetic Appeal

Although passive solar buildings may look different than their more conventional neighbors, their appearance is generally considered appealing. The nation has become accustomed to the use of large expanses of glass and often chooses such a design for aesthetic reasons. Many architectural features such as picture or clerestory windows and massive fireplace sections in a building can be turned to good thermal use simply by properly establishing their relationship to the building geometry and orientation. Many thermally desirable features such as shading overhangs and shutters can add to the building's architectural variety. The availability of sunlight within the living space opens the possibility of adding growing plants to the space for the simple joy of their beauty, variety and ever-changing characteristics.

Although architectural design has never been static, the advent of passive design approaches adds a whole new dimension and synergy to building design which will herald a revolution in architectural practice.

Independence

Even in the event of total failure of the backup heating supply and the electrical service to he building, a well-designed passive solar building will remain moderately comfortable and will never freeze.

PERFORMANCE SIMULATION AND EVALUATION

The Los Alamos Scientific Laboratory (LASL) program has been a cornerstone of the Department of Energy research and development in passive solar heating. The primary objectives are 1) to perform a detailed evaluation of passive solar heating and 2) to provide a quantitative procedure which will enable building designers to incorporate passive solar heating into building design. The program consists of four key elements: a) experiments in passive solar test rooms, b) monitoring of passive solar buildings, c) computer simulations and system analysis of passive solar concepts, and d) development of design tools for incorporating passive solar concepts into building design.

Test Rooms

Fourteen passive solar test rooms have been constructed at Los Alamos and detailed data have been taken under very carefully controlled conditions. Based on these results validation of the computer simulation models for thermal storage wall and direct gain test rooms has proceeded on schedule.[6,7] Future work will concentrate on different design approaches such as convective loops, attached sunspaces, and thermal storage roofs, and on the extension of these experiments to a variety of advanced concepts to improve performance.

Monitored Buildings

Instrumentation has been installed in 15 passive solar buildings and extensive data have been taken during two winters' operation. These buildings represent a variety of design approaches. Data taken on these buildings allow the extension of the computer model validation from single-room test situations to actual buildings having a variety of complicating factors due to the more complex structure and the occupancy. Data from three buildings have been analyzed and the model validation process has been successful.

Computer Simulation and Systems Analysis

The experimental and monitoring work is tied together and made useful by computer simulation and analysis. Only through these tools can the results be generalized, design methods developed, and the effect of both climatic factors and design factors quantified. The most progress has been made in this area. Once faith has been established in a mathematical modeling approach, then a complex computer model can be assembled representing a particular class of buildings and this model used for systems studies. These are of two types: climatic studies and parameter variations. These studies have been the backbone for the LASL effort.

The results of these studies have confirmed that passive solar heating is practical throughout the range of climates within the United States. The performance variation between different climate zones is less than might have been imagined since passive solar is shown to work effectively in relatively diffuse solar conditions. When coupled with an economic evaluation, it has been established that passive solar heating competes favorably in 1978 on a life-cycle basis with electric space heating in nearly all parts of the United States, with oil in most places, and with (regulated) natural gas in some places.

The approach used is to perform full-year hour-by-hour simulation of the buildings for various design possibilities for 29 different climates for which LASL has detailed weather and solar data. The hour-by-hour simulation techniques can also be used to determine the influence of various design parameters. On this basis important performance and economic decisions can be made in order to choose the most appropriate systems for each climate and to optimize the designs.

DEVELOPMENT OF DESIGN TOOLS

LASL has made significant progress in using the complex models to develop simple design techniques. To do this the results of many hundreds of hour-by-hour analyses are used as a basis for determining correlations. This has been carried through to completion for two classes of passive designs and is underway for the additional classes. The procedure was used successfully as the basis for evaluation of the recent Passive Solar Design Competition and Demonstration.

Simplified Method

The technique employed is the LASL Monthly Solar Load Ratio method. The procedure is to determine for each month of the heating season a dimensionless Solar Load Ratio (SLR) defined as:

SLR = (monthly solar radiation absorbed)/(monthly load).

The monthly solar radiation absorbed is the total solar energy transmitted through the collection glazing less any that is reflected back out. The monthly load is the total monthly heating requirement of the building in the absence of any sur , including heat required to satisfy the steady-state load of the solar collection wall and building infiltration.

It has been determined that the monthly Solar Savings Fraction (SSF) can be successfully correlated with SLR. Since the monthly SSF may vary statistically for the same value of SLR, the recommended procedure is to estimate b on averages. Month-to-month variations will tend to average each other out and the SLR method will provide a good estimate of the long-term average. The method characteristically produces annual solar savings fraction estimates which fall within a 3.4% standard deviation of the hour-by-hour annual calculations.

The correlation curves for SSF vs SLR do not depend on climate (the correlations are done for 10 to 29 widely differing climates in the U.S. and Canada) but do depend on system type. Correlation curves have been generated for direct gain, Trombe walls, and water walls[3] both with and without night insulation. Exponential functions have been used for the correlations.

For each month of the heating season, the ratio S/DD is determined, where S is the total monthly solar radiation transmitted through one square meter of south-facing vertical double glazing and DD is the base 18.3 C heating degree days.

Then the Solar Savings Fraction (SSF) is determined for each month as follows:

$$SSF = 1 - K\,(1-F), \text{ where}$$
$$F = A\,X, \text{ for } X < R$$
$$F = B - C\exp(-DX), \text{ for } X > R$$
$$F \leq 1.000 \text{ for large } X.$$

and where

$$K = 1 + G/LCR$$
$$X = (S/DD)/(LCR \times K)$$

(X is the "Solar Load Ratio")

$$LCR = \frac{\text{building load coefficient, exclusive of solar glazing}}{\text{solar collection area}}$$

(LCR is the "Load Collector Ratio")

Constants for the various passive system types are as follows:

	G	R	A	B	C	D
DG	10.6	0.5	0.5213	1.0133	1.0642	0.6927
DGNI	2.4	0.7	0.5420	.9866	1.1479	0.9097
TW	3.6	0.6	0.3698	1.0408	1.0797	0.4607
TWNI	0.5	1.0	0.4556	.9769	1.2159	0.8469
WW	5.0	1.3	0.4025	.9872	1.5053	0.9054
WWNI	0.7	1.2	0.4846	.9799	1.8495	1.2795

The annual SSF is then obtained from the sums of the monthly values, as follows:

$$\text{Annual SSF} = \frac{\sum_i SSF_i \times DD_i}{\sum_i DD_i}$$

Here, DG, TW, AND WW indicate direct gain, Trombe wall, and water wall respectively. NI indicates night insulation.

Most passive designs consist of a mixture the basic approaches. Few Trombe walls are without some direct gain component. Most water walls are spread-apart tubes or other containers which allow some direct heating. The recommended procedure is to compute a single SLR, based on the total solar gain through all glazing divided by the total thermal load, and then compute a weighted-average SSF. This is determined by computing a separate SSF for each design approach and averaging between them based on the relative proportion of each glazed area.

Reference Designs

The correlation curves are determined for a set of "reference" configurations defined as follows:

> Double glazing, normal transmittance = 0.747 , 6.4 mm spacing
> Night insulation (when used) is 0 63 W/^{o}Cm^{2}; 5:00 pm to 8:00 am
> Thermal Storage = 920000 J/^{o}C per m^{2} of glazing
>   Water wall: equivalent to 216 mm of water
>   Trombe wall: 450 mm thickness
> Thermal conductivity = 1.73 W/m^{o}C
> Trombe wall has vents, upper and lower, each 3% of the wall area, having backdraft dampers.
> Direct Gain = exposed surface = 3 x glazed area
>   150 mm thickness
> Other building mass is negligible
> Wall-to-room conductance = 5.7 W/^{o}C m^{2}

Auxiliary maintains an internal building temperature above 18.3^{o}C. Heat is dumped to maintain the building temperature below 23.9^{o}C. No internal building heat generation.

Estimating the Effect of Variations in Design Parameters

The effect of changing a design parameter (other than the area of glazing) can be assessed by studying the published results of hour-by-hour calculations in which the various parameters are varied one at a time. These are given in Reference 8.

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